

Department of Metallurgy and Materials Science
McMaster University
Hamilton, Ontario

CONTRACT REPORT NO. OSU 82-00170

Annual Progress Report on
The Development of Nondestructive Testing Techniques
to Evaluate the Integrity of
Sintered Solid-State Electrolytes - Phase II

July 1, 1982 - June 30, 1983

Patrick S. Nicholson

Research Associates:

J. van den Adel
A. Stockman
Dr. N.D. Patel

Research Contract DSS

20SU 23440-2-9065

For

Dr. T. Wheat
Energy, Mines and Resources

June 1983

I INTRODUCTION

This report is divided into the broad divisions defined in the Work Statement (July 82 - June 83). Where possible, progress in those specific areas will be reported. In some cases this involves the continuation of work previously reported on and in others, it involves reporting on work initiated in this report year. In the former case, the sections will be brief.

II MODEL DEFECTS IN GLASS

As much of the annual report (1981-82) dealt with these studies, only developments of this year will be briefly reviewed.

By June-July 1982 the supply of regular glass defects obtained from Pilkington/Ford had been studied to exhaustion. An arrangement was made with the company to introduce prepared defects into their glass ribbon during a period of changeover when the ribbon was scrap anyway. To this end, mixed powders of Al_2O_3 , SiO_2 and ZrO_2 were prepared with size ranges 30 μm , 38-42 μm , 75-104 μm and 104-150 μm . These powders were diluted with ground glass so as to reduce the total number of defects per unit volume of glass ribbon to levels where they could be studied individually.

Samples of each diluted powder were selotaped to the end of a long iron rod and held over the centre of the molten glass ribbon. The tape burned away and the particles entered the glass ribbon. A large number of "lights" of glass were produced in this way. One third of these were shipped to McMaster for examination, the remaining two-thirds are still on the floor at Pilkington-Ford awaiting a decision on their value to the programme.

Each "light" was cut in four and recently wooden boxes have been constructed for easy manipulation of these samples. Edge lighting inspection was used to conduct a preliminary examination of the quarter lights. Most defects were found to be surface located but a number of apparently-internal defects were detected. On closer examination, a number of these were found to be surface defects. The problem was determined to be the size of the $\frac{1}{4}$ -light being too large to allow specification of defect location when the defect in question was far from the edge-of-examination. With this in mind, the $\frac{1}{4}$ -lights will be further cut and polarised light will be used to examine the defects. The final glass samples will be exactly the size required by the newly-constructed scanner

and its commissioning will reinitiate the glass-defect examinations. These model samples will be used to put the new scanner and its systems through their paces and to evaluate the new transducers being developed as part of this program.

Another interesting parallel investigation that is underway in the NDE group is the subject of a Masters thesis study by Mr. M. van Harten. Laboratory melts of glass have been impregnated with a series of defects with differing acoustical properties. The defects which have been introduced are nickel spheres ($\sim 100 \mu\text{m}$) and zirconia and hafnia particles. These defects are sparse and internally located. These samples can be characterised optically and ultrasonically. Complementary to these samples, the same type of Ni-spheres have been hot pressed into magnesium fluoride polycrystals. The opacity of these samples defeats optical characterisation but the location of the nickel spheres has been determined by x-rays so they can be ultrasonically characterised. This system is a model polycrystalline ceramic and as such, study constitutes the next logical step between glass-defects and defects in actual high-performance ceramics. The status of this study is as follows:

- the samples are made
- a computer program has been written to generate the defect spectra from the US scans
- an approximate physio-mathematical model (see later in this report) has been developed which can predict the spectra from the inclusions
- it is planned to compare the predicted and experimental defect spectra to identify any interconsistencies.

III THE SAMPLE MANIPULATOR AND PDP11 COMPUTER

This section starts with a review of the new sample-manipulator and continues with details of developing its compatability with the PDP11 computer. In the previous year, existing equipment was pushed forward to the limitations of the instrumentation. This culminated in a presentation in Montreal in May 1982 and an article in the CSNDT Journal in November 1982.

Since then attempts have been made to improve equipment, to eliminate inadequacies and improve signal clarity. A major piece of badly needed equipment was a high precision scanner (Fig. 1).

The scanner has a very stiff main frame which will not distort under the weight of the bridge. The bridge is moved by a leadscrew (X-direction) which is driven by a stepper motor which in turn is controlled by a mini-computer (Fig. 2). There is also a z-axis motor-driven control but this is driven directly from the main computer. The motor is hidden inside the test wand

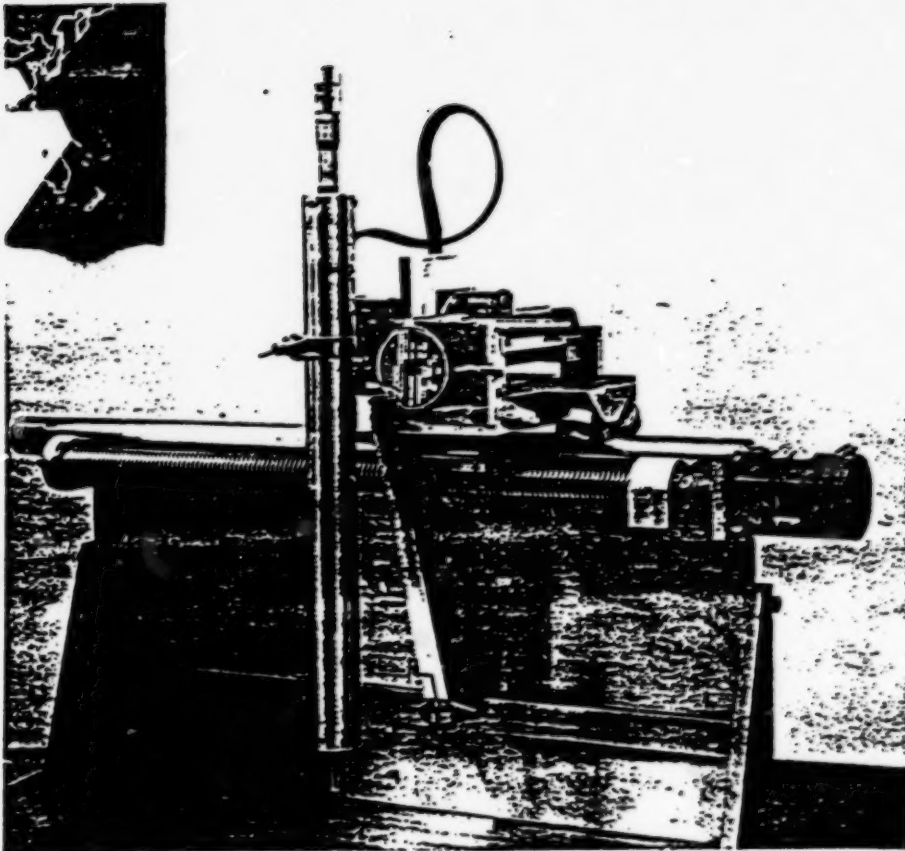


Figure 1

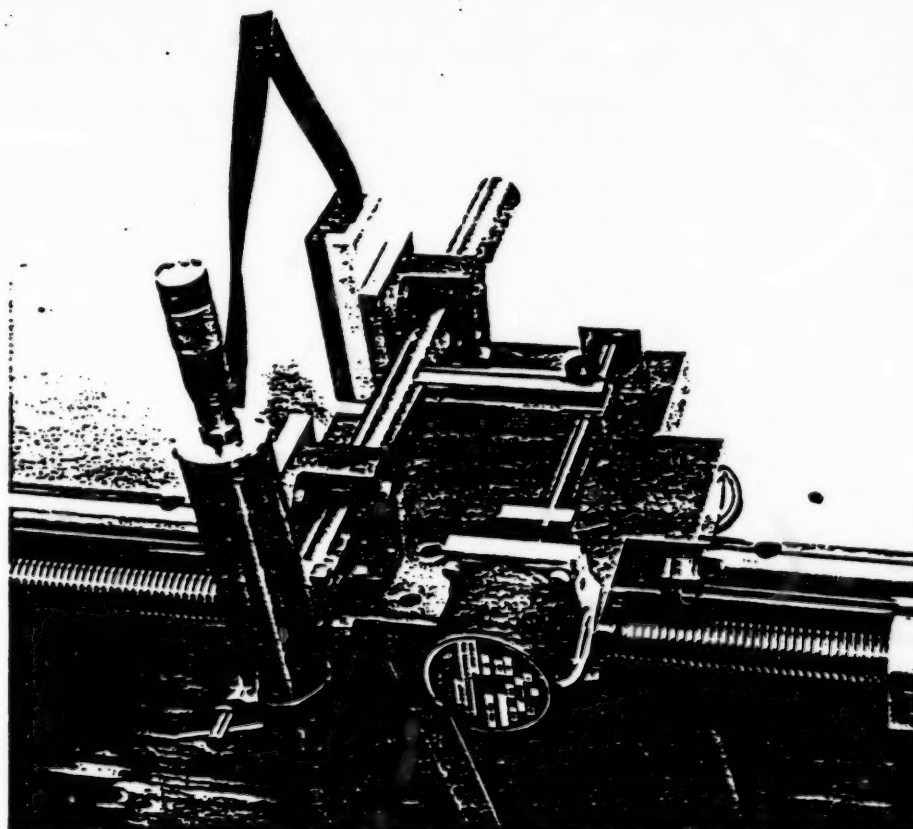


Figure 2

shown in Fig. 1.

Scanning is accomplished by motion in the X-direction. At the end of each scan, the Y-axis motor moves a small amount (say 0.08 mm) until the entire X-Y plane is covered. Only then is the Z-axis activated in order to resume the scan of the next layer. It is obvious that the Z-axis activity is extremely low and could easily be added to the main computer program.

The main reason for the mini-computers is the high demand on their activities, i.e., if a flaw is found, the position has to be registered in the memory of the main computer along with the flaw size. Since the main computer is not responsible for pulses to the stepper motor, the memory is free for flaw registration.

The stiff construction of the main frame allows a rigid support for the bridge which is also of solid construction. A relatively light weight search wand (in spite of its built-in motor) avoids whipping of the transducer at sudden starts and stops. There is a provision for fine alignment of the transducer for perfect 90° beam entry. Manual X and Y movement is still by means of the stepper motors, but overridden by toggle switches. The Z-axis has a manual micrometer in addition to the drive motor.

Detailed links with the main computer, cables and cards have yet to be made and the existing program has to be modified and updated for Z-axis control.

Under the present (soon to be former) system of scan control (Figure 3), the computer is responsible for generating the pulses which result in the stepping motors advancing one position. The advantage of this system is that the relative position of the transducer over the sample is known at all times. In the event that a defect is detected, the computer may be signalled to place the values of the X and Y axis counters in a buffer. The greatest drawback is that the operating system must be interrupted by a clock once for every step pulse required. This limits the speed at which the scanner can travel. Using the timer clock available on the PDP11/23 processor board operating under RT11, the maximum pulse rate is 60 Hz. This gives a speed of 1.25 mm/sec which is far too slow for practical scanning.

The desired scanning rate for the new system is 50 mm/sec (2500 pulses per second). To achieve this, a separate microprocessor-based controller has been designed and built specifically for use with our system by TECHNO-SCIENTIFIC INC. of Toronto (Figure 4). Driving speed, acceleration scan length and width will be set by the computer interfaced over the General Purpose Instrumentation Bus (GPIB). The relative position of the scanner will be kept in the memory

Figure 3

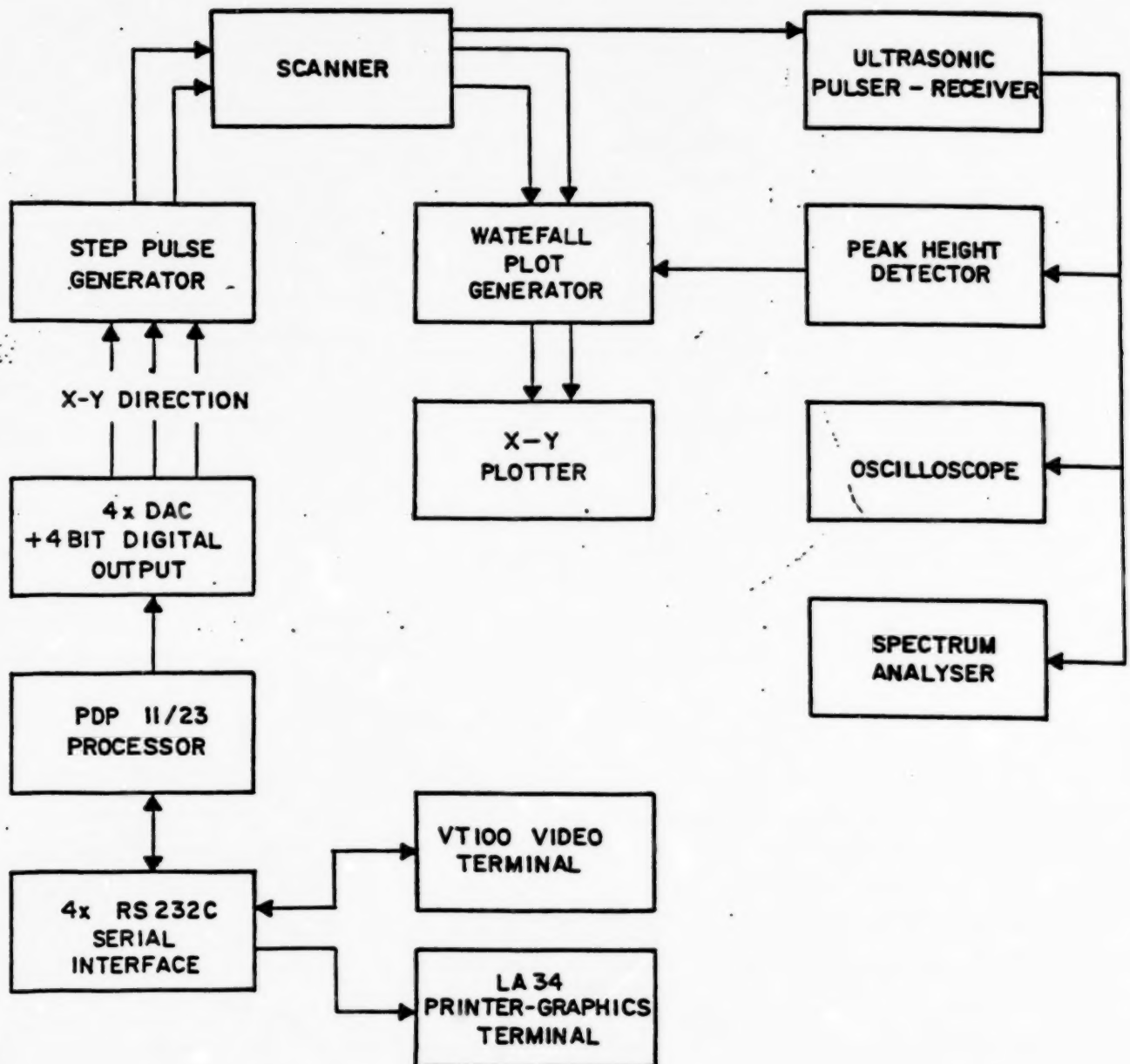
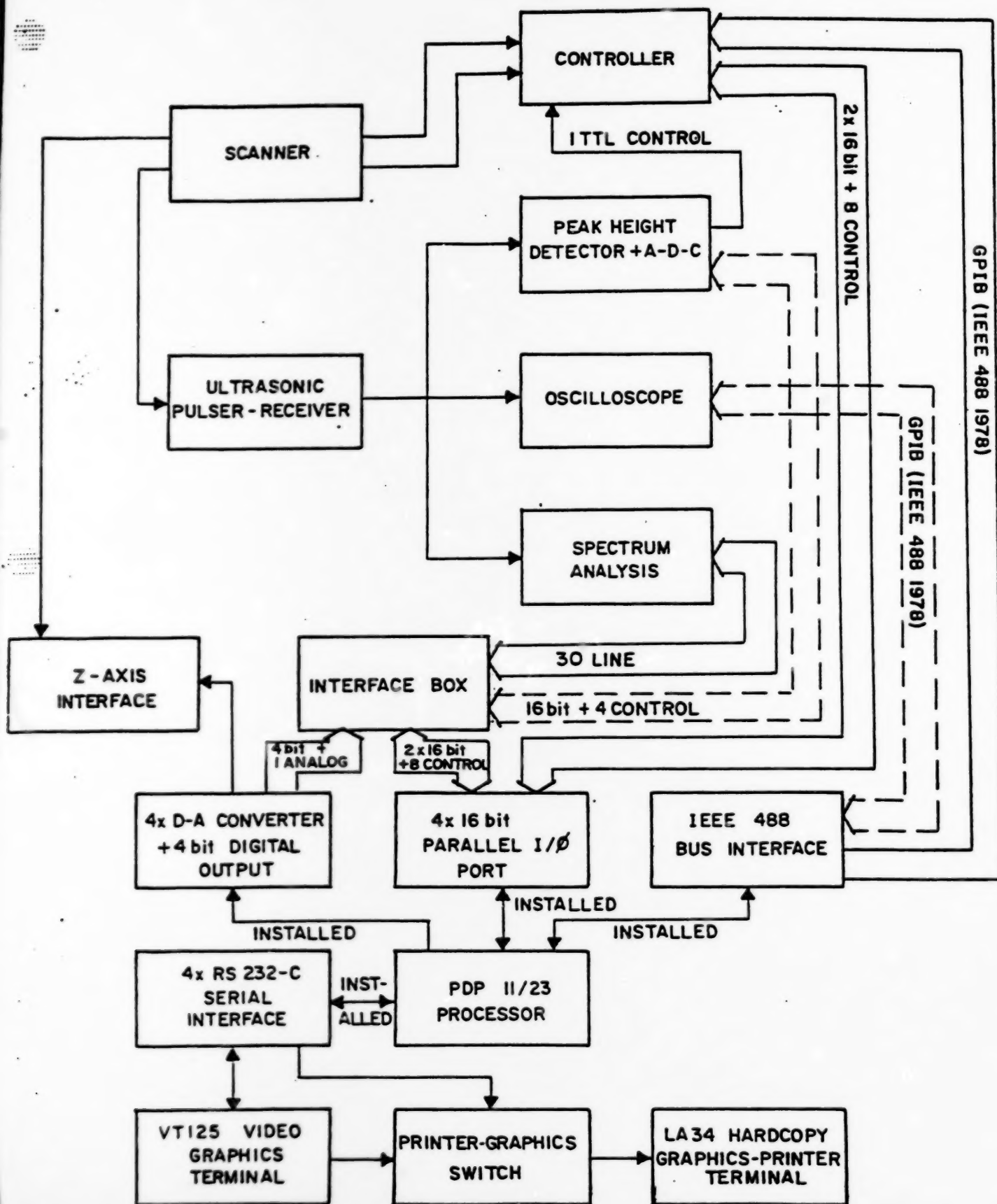


Figure 4



of the controller and will be made available to the computer over 2 x 16 bit parallel I/O ports. This information can be obtained from the controller either by a request from the host computer (PDP11) over the GPIB or whenever some external event triggers the controller. For our purposes this event will be a 5 volt TTL pulse which occurs when some preset level within the peak height detector has been exceeded. This will usually occur whenever reflection of an ultrasonic signal by a flaw has occurred.

The controller has command of the X and Y axes of the scanner for which high speed scanning is required. The Z axis however, is moved only once per scan or whenever a defect has been located to be analyzed. Thus the host computer will be in charge of its motion through a Digital to Analog converter within the computer.

The Polarad Spectrum Analyzer is interfaced to the computer via 2 other 16 bit parallel I/O ports through an interface box which controls the data flow using 4 x 1 bit lines and one analog line. Thus the computer can acquire the reflected signal amplitude spectrum for analysis. The interface box will also control the flow of data from the digitized peak height signal through the same 16 bit parallel I/O ports. As well, a high speed digitizing oscilloscope is projected to be linked to the computer via the GPIB for direct signal acquisition.

Waterfall plots of the scan showing the defect location and amplitude can be generated on the Digital VT125 video graphics screen and later passed on to a hard copy Digital LA34 terminal. The FORTRAN IV equivalent program for this appears in the Appendix labelled Computer Programming.

This completes the present equipment configuration set up over the past 12 months. Much of the development has been toward automating the system by placing it under the control of the PDP 11/23 minicomputer obtained previously.

IV TRANSDUCER DEVELOPMENT

In this section, the development of the sintered (hot-pressed) ceramic and crystals therefrom is summarised.

The basic aim of the work is the development of ultrasonic compressional wave transducers in the range 20-100 MHz frequency. Ultrasonic transducers (without incorporated delay lines) of frequencies 20 - 100 MHz, with broad-band width and operating in the fundamental modes, or odd multiple excited modes, in the above range are not available commercially. Two transducer production techniques have been explored;

- (1) the sputtering of ZnO and PZT on planar and shaped (focussed) slugs.
- (2) the polishing and poling of PZT 4, PZT 5 and SPN discs of $100\mu\text{m}$ thickness.

The sputtering was undertaken by Queens University. For the frequency range of present interest, i.e., 20 - 100 MHz, the thickness of the sputtered film should be 20-100 μm . To date, the maximum thickness achieved by Queens University is $\sim 8\mu\text{m}$, which corresponds to ~ 250 MHz. The curved shaped slugs were sputtered with ZnO. These transducers rapidly short-circuited under the applied voltage. Planar transducer slugs were made from stainless steel and brass material (Fig. 5). The front face of the steel slugs will be sputtered with PZT. Most properties of these thin films resemble those of the bulk PZT material.

The second phase of the program was to grind and pole thin PZT discs of thicknesses in the range 20-100 μm . PZT 4 and PZT 5 sintered ($\frac{1}{2}$ " diameter x $\frac{1}{2}$ " length) rods were obtained commercially (Almax Industries). Thin discs were cut and lapped to thicknesses in the range 150-180 μm , using 600 grade silicon carbide grit. The large-grain-size material suffered pull-outs during lapping and a refined technique of thinning down the discs was developed. Grinding PZT discs thinner than 100 μm can now be done routinely. The technique involves the use of a fine-diamond cup-wheel. Discs greater than 110 μm were successfully poled in peanut oil in a specially designed sample holder at 100-125°C with a DC field of 2600-4000 v/mm. (The newly-acquired high voltage generator is capable of generating a DC field of 12 kv). However, for discs $< 110\mu\text{m}$, the flaws in the PZT became total break-down paths when poling voltages were

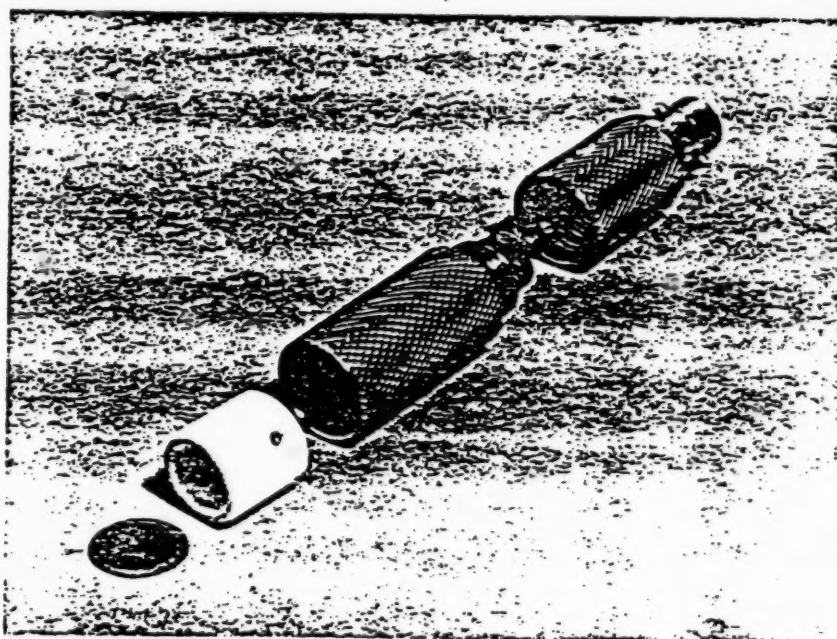


Figure 5

applied (2000-2700 v/m and 3000-4000 v/mm for PZT 4 and PZT 5 respectively).

The resultant cracks were investigated and were found to always occur from large defects in the microstructure. These defects were present in almost all the PZT 4 and PZT 5 discs made from the $\frac{1}{2}$ " slugs supplied by Almax. The size of the defects varied from 50-120 μm . SEM x-ray analysis indicated that they were flakes of PZT with a thin covering layer of iron. It is speculated that they are formed during ball or hammer-milling in the process of raw material or calcine comminution. The need for a better base material was evident.

PZT 4 powder was obtained from Almax and two different batches of discs were made. The first batch was made from the as-received powder and the second from sieved as-received powder. These discs were isopressed at 40,000 lbs and sintered in the range 1170-1300°C. The discs made from the sieved -400 mesh powder were free of defects whereas discs made from the unsieved powder showed the same defects as the PZT slugs previously obtained from Almax. A typical photograph of the cracked microstructure after poling is shown in Figure 6A and 6B. The good discs still were restricted to $\sim 80 \mu\text{m}$ thickness because of porosity. It was therefore decided to optimise the sintering conditions and explore PZT 4 fabrication by hot-pressing.

More PZT 4 discs were isopressed at 50,000 lbs. and a series of experiments were performed. For sintered discs, the following conditions were found to optimise the piezoelectric properties;

Heating rate 433°C/hour
Cooling rate 325°C/hour
Sintering Temperature - 1300°C
Soaking Period - 1 1/2 hours
Surrounding Media - sintered PZT powder
 sieved - 200 mesh

Densities of 7.6-7.8 g/cm³ were obtained, the former with no binder, the latter with PVA. These values are better than the commercial material with densities 7.5 g/cm³. The sintered materials had a relative dielectric constant of 2400 @ 1 KHz, whereas the dissipation factor @ 1 KHz was $\sim 1.5\%$. The planar coupling coefficient was found to depend upon porosity, grain size, poling field and temperature. Thin discs with > 10 MHz frequency, posed difficulties vis à vis measurement of resonance and anti-resonance frequencies and for evaluating their K_p values. These difficulties are associated with reflections due to the mismatched impedance of the oscillator and transducer using the simple resonance method. An improvement in this technique, mainly on the instrumentation side has been

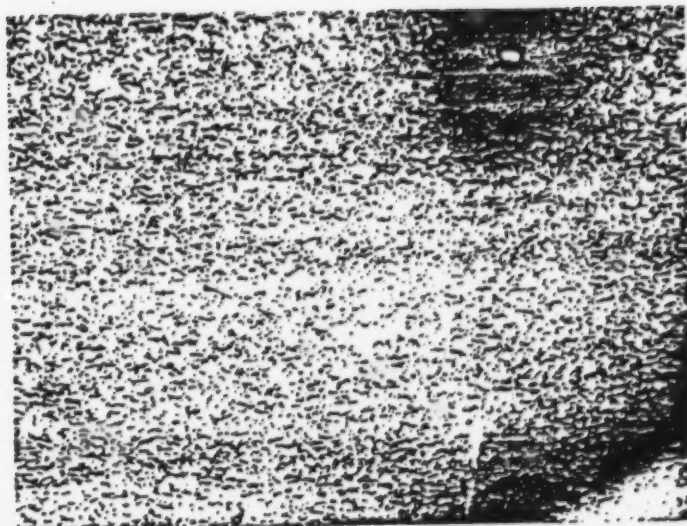


Figure 6A

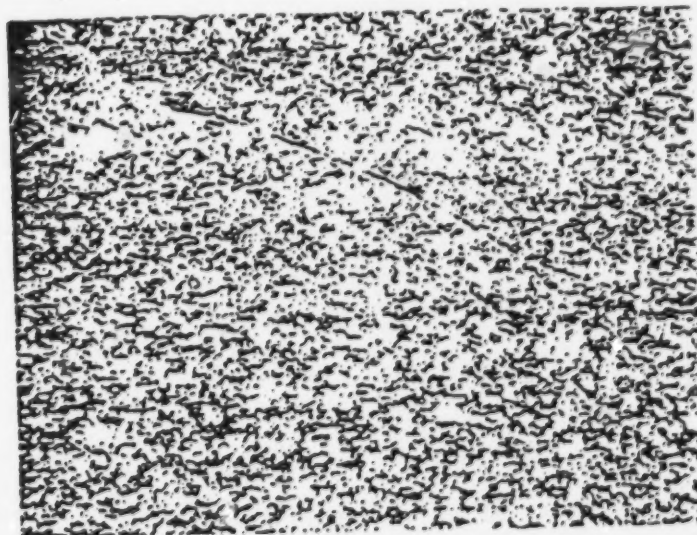


Figure 6B

investigated. For this reason, the signal-to-noise ratio of the 1st back reflection was measured using a steel specimen 3 mm long and 1.6 mm in diameter. The poling temperature was 100°C and the poling time 25 mins. On increasing the temperature to 120°C, no effect on poling behaviour was noted. The resultant plot is shown in Figure 7. The variation of attenuation with frequency was not considered in this case.

To eliminate the porosity, it was decided to make PZT 4 discs by hot pressing. The aim of this phase of the project was to explore the technique of hot pressing for obtaining a density close to the theoretical value whilst controlling the grain-size to 1-5 μm . Grain sizes $< 1 \mu\text{m}$ are undesirable due to problems of retaining strong ferroelectric behaviour. To this end, a special cooling system was built for the hot press. High temperature molds (graphite) and shielding systems were also fabricated. For these experiments, different conditions (temperature, pressing time, pressure, surrounding media, etc.) were explored to obtain the optimum conditions for hot-pressing PZT discs. Before studying the microstructure (deficiency of oxygen, composition, etc.) of these hot-pressed materials, it was necessary to remove the diffused carbon from the material. These hot pressed discs were cut to 200-500 μm and heat-treated in air for 3 days at $\sim 850^\circ\text{C}$. The homogeneous removal of carbon was not accomplished for discs of density 99-100%. Higher temperatures ($> 850^\circ\text{C}$) cannot be applied because of the Pb content which will oxidise. Oxygen deficiency can be avoided by covering the pellets with a mixture of Al_2O_3 and PZT powders.

SPN material (obtained from Almax) was pressed in a graphite mold at 1080°C and a pressure of 4000 psi for 20 min.; it had a density of 4.54 g/cm^3 . A heat treatment was used to remove the carbon picked up from the graphite mold, estimated at 0.2 to 0.3 w/o. Thin discs of SPN (100-200 μm) were poled successfully. Optimum poling conditions for this material were 160°C temperature and a DC field of 2000 V/mm. The dielectric constant @ 1 KHz was ~ 900 and the dissipation factor @ 1 KHz was $\sim 5\%$.

To avoid the carbon contamination associated with graphite molds, a molybdenum hot-press mold has been fabricated. Different PZT powders have now been obtained from Ultrasonic Powders. The PZT 4 series were sintered at 1320°C . Thin discs will be made from this material. The densities of this series of PZT compares favorably with values quoted by Ultrasonic Powders. These PZT 4 powders and PZT 5 and PZT 7 will be hot pressed and the properties

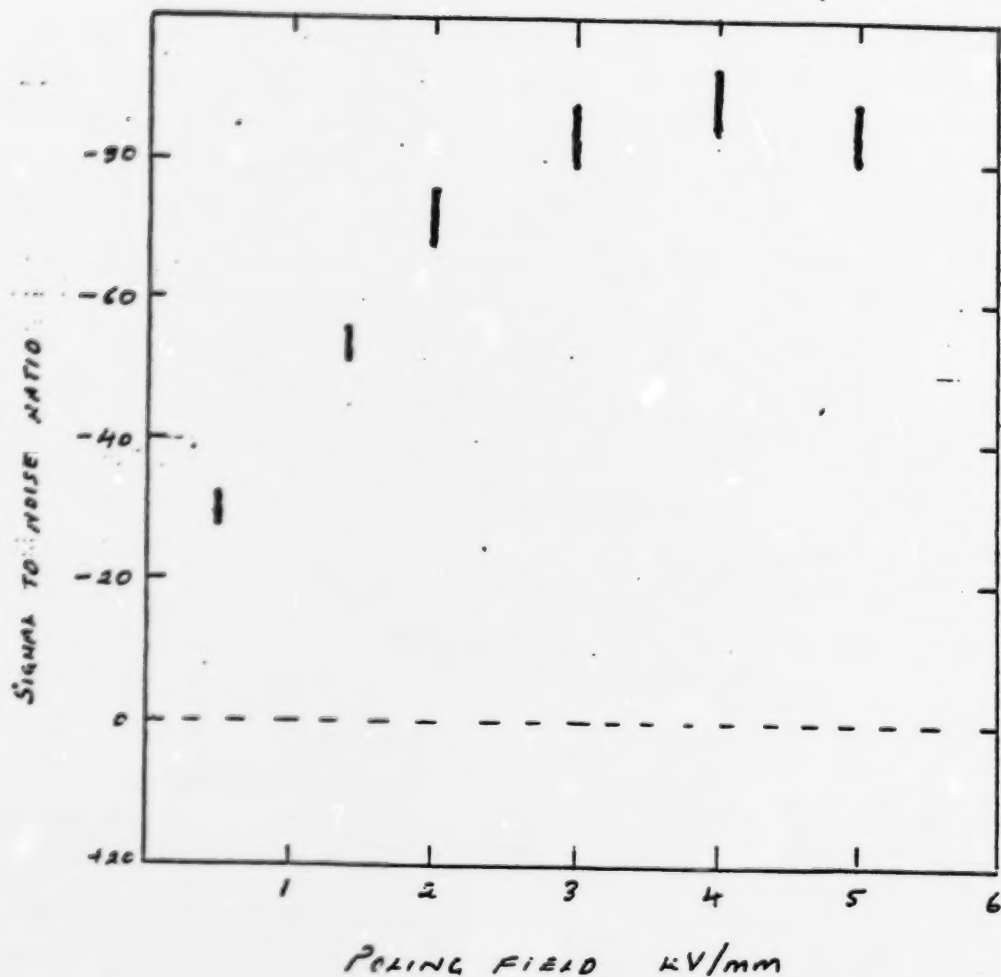


Figure 7 Effect of poling field on signal to noise ratio for PZT 5 specimen of different thicknesses.

of the resultant pellets will be compared with the sintered materials. These sintered materials were defect-free (cf the PZT of Almax).

To incorporate these discs into transducers housing designs have been made and are shown in Figure 8A and 8B.

The teflon part will be filled with epoxy (Araldite) mixed with tungsten particles. PZT discs of thickness 200-300 μm with electrode configurations shown in Fig. 8, will be bonded to the teflon, then ground down to the required thickness. The teflon piece will be fixed in the housing and a thin film of conducting metal will be evaporated onto the front face. An appropriate epoxy will be placed on it and, with aid of a ball bearing press, lenses will be made.

A 30 MHz damped transducer of exceptional power has been made of PZT 4 and is shown in Figure 9. Its signal output is shown in Figure 10.

V STUDIES ON INFLUENCE OF CABLE LENGTH ON THE PERFORMANCE OF A FOCUSED 25 MHz TRANSDUCER

Much has been said in the literature and elsewhere, on the influence of cable length on transducer performance. This was studied as follows.

The following results which were obtained when an ultrasonic pulser 5030A was compared with 5052 pulser (Panametrics). The amplifier bandwidths are 1-100 MHz and 1 KHz-30 MHz respectively. The first reflection of an inclusion in a glass plate was monitored using a 25 MHz focussed transducer. The cable length between the transducer and the instruments was varied. The following conclusions were reached:

- (1) there was little difference in the amplitude of the signal from the inclusion, in both cases. However, the 5052 UA gave smoother pulses (Figure 11).
- (2) the centre frequency of the reflected signal from the inclusions (using the "25 MHz" focussed transducer) was 27 MHz and 32 MHz using the 5030A and 5052UA respectively.
- (3) the main bang (initial pulse spike) of the 5030A showed a 10ns bandwidth without the transducer load and a 20ns bandwidth when loaded.
- (4) the 75 MHz and 100 MHz delay-line transducers supplied by Panametrics showed 40 and 50 MHz centre-frequencies when the back reflection echoes from an attached delay-line quartz-rod were inspected (Figure 12).¹⁶ The first two reflections showed the component of the main bang, i.e., a spike rather than oscillatory echoes. There was no improvement when different cable lengths were used.

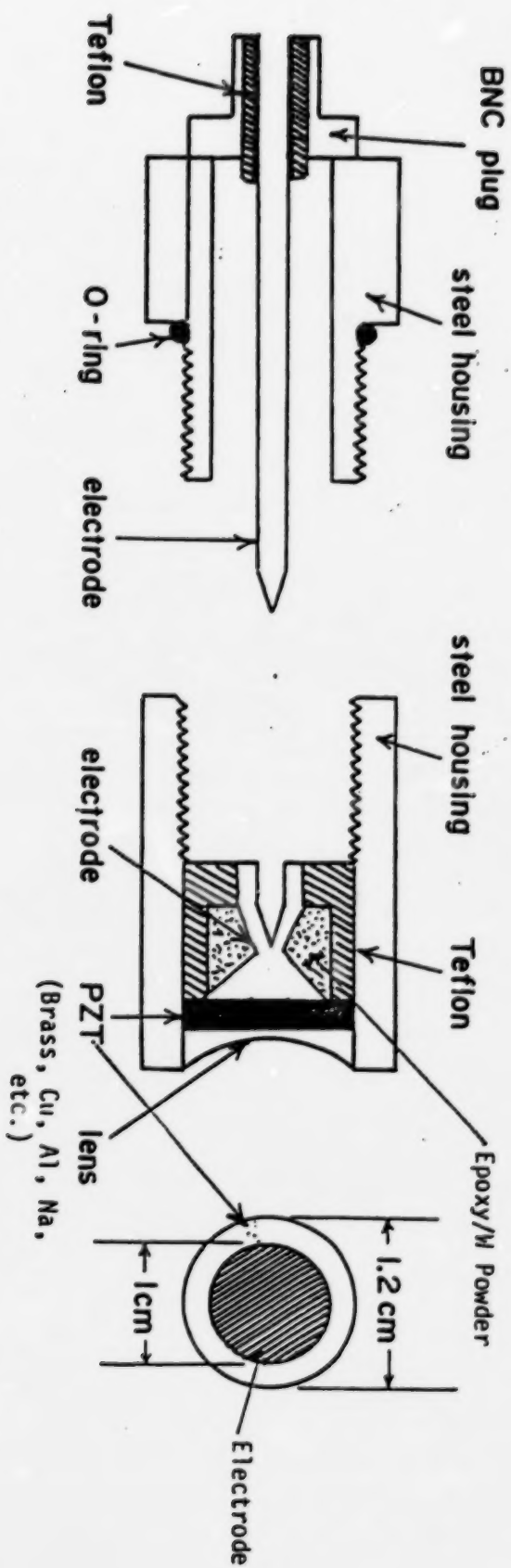


Figure 8A

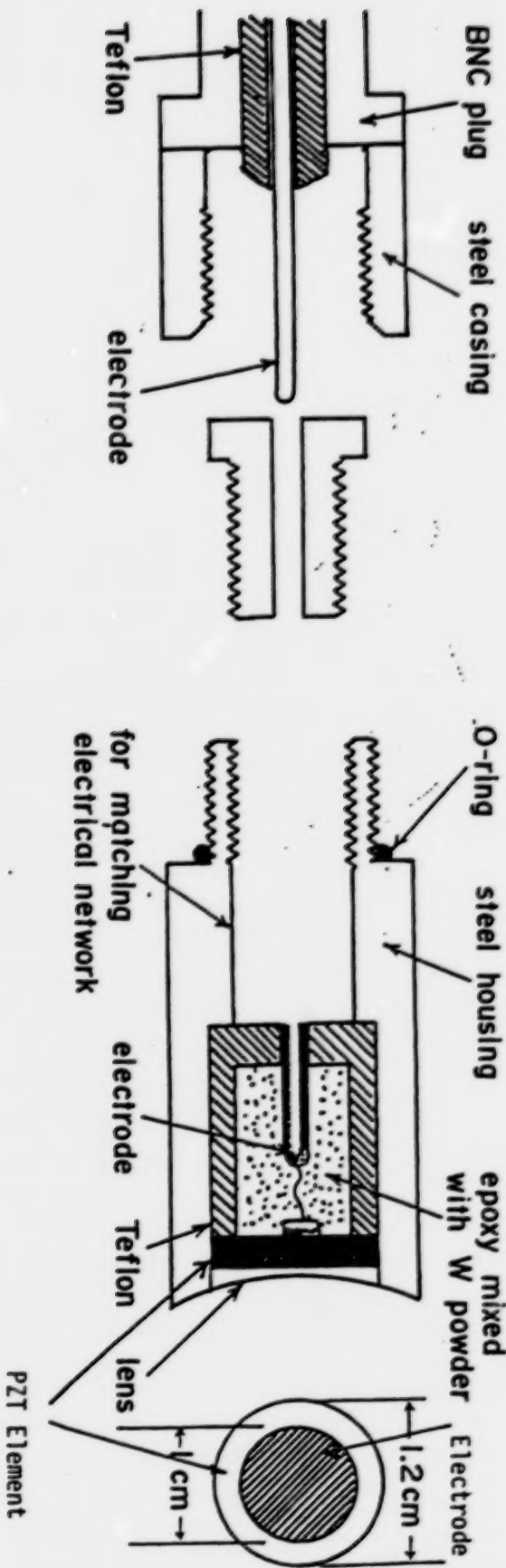


Figure 8B

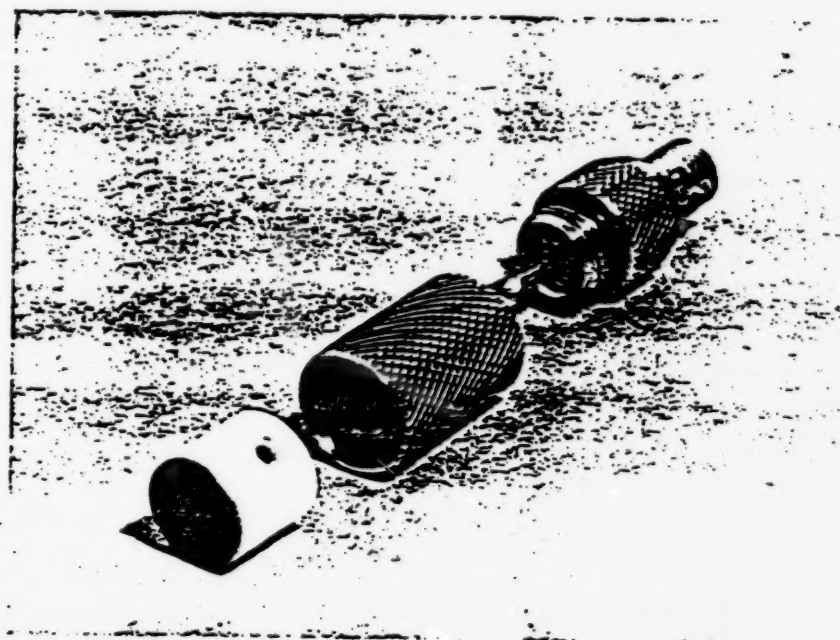


Figure 9

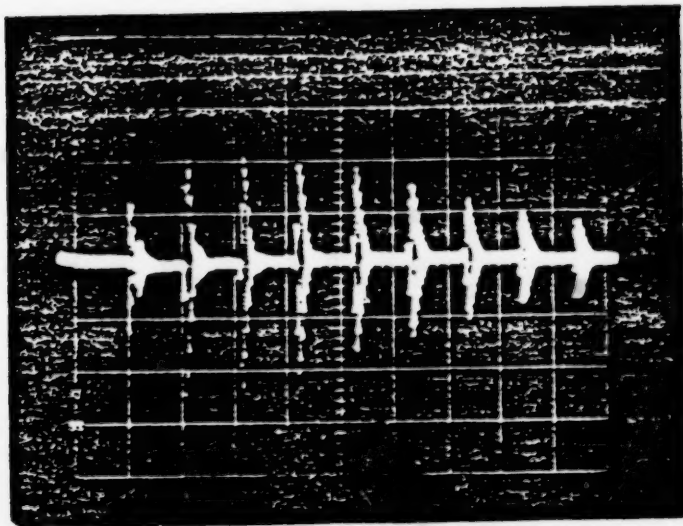


Figure 10A

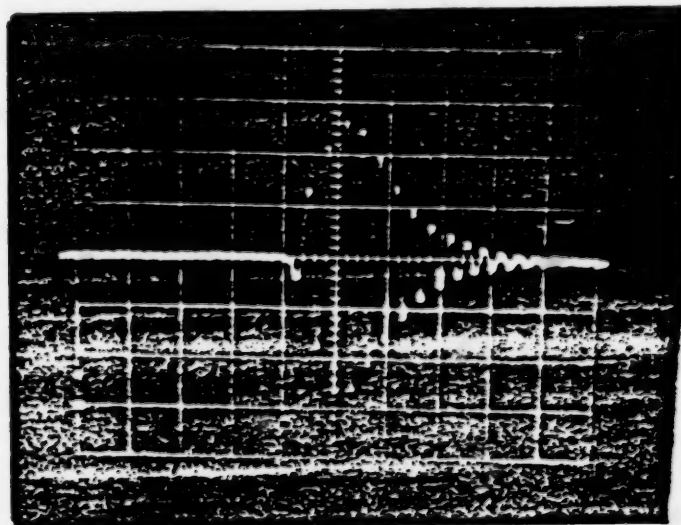
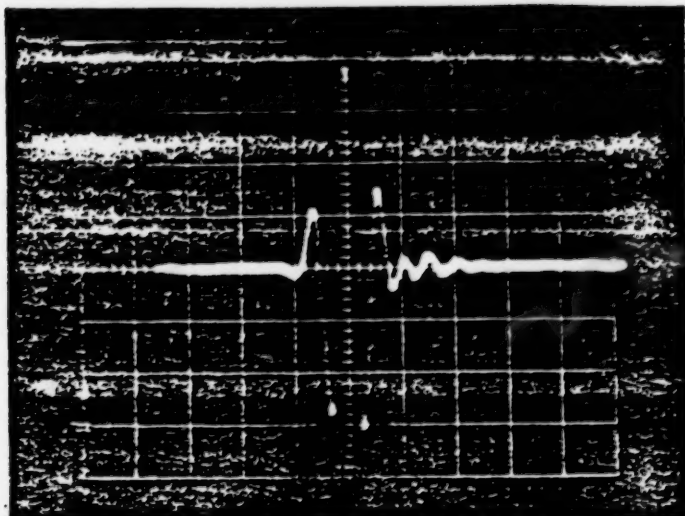
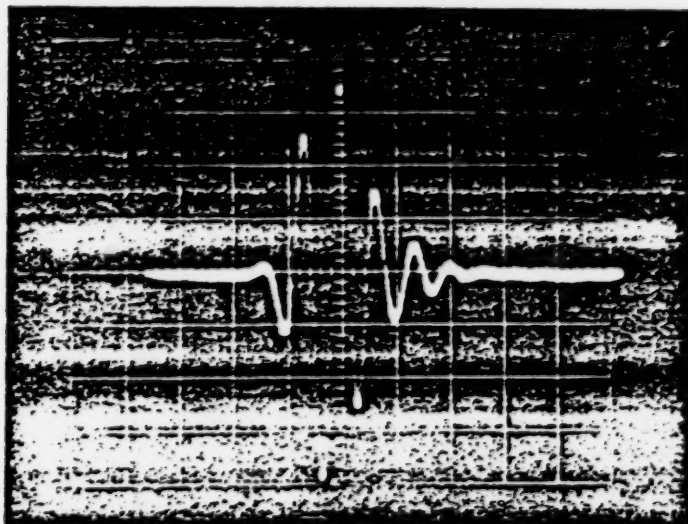


Figure 10B



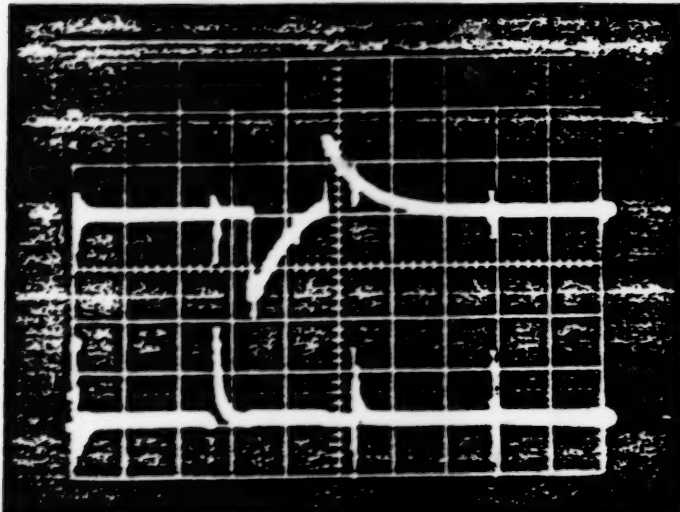
11A

5030A Pulser (2)
 Sample 15 Defect
 Time Base = 50 ns/div
 Vertical = 20 mV/div
 Damping = 500 , AT.L. = 2dG
 Frequency = 31.64 MHz
 Probe =
 Cable Length = 155 cm
 820916-2



11B

5052UA Pulser
 Sample 15 Defect
 Time Base 50 ns/div
 Vertical 20 mV/div ENG-1
 Damping 500 AT.L. 2dG
 Frequency = 27.78 MHz
 Probe 32 MHz
 Cable Length = 155 cm
 820916-6



12A

5030A Pulser

75 MHz Delay Probe

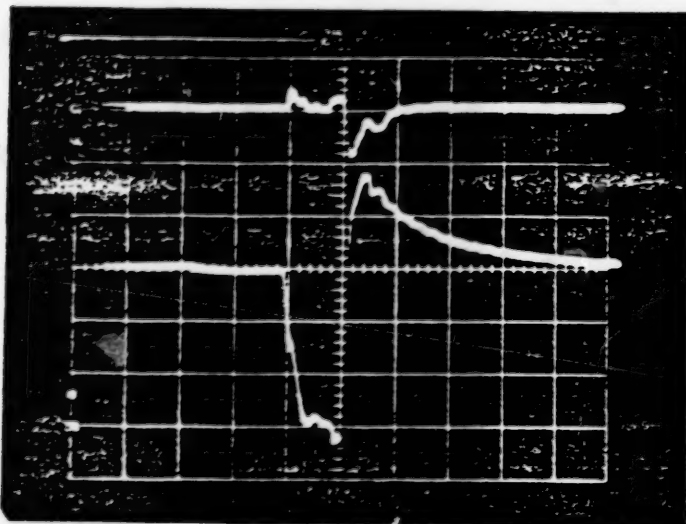
Cable Length = 7 cm

Upper Trace-Gated rf 50mV/div

Lower Trace-Marked rf 0.5V/div

Time Base 1 s/div

Damping 5-0 AT.L. 2 db

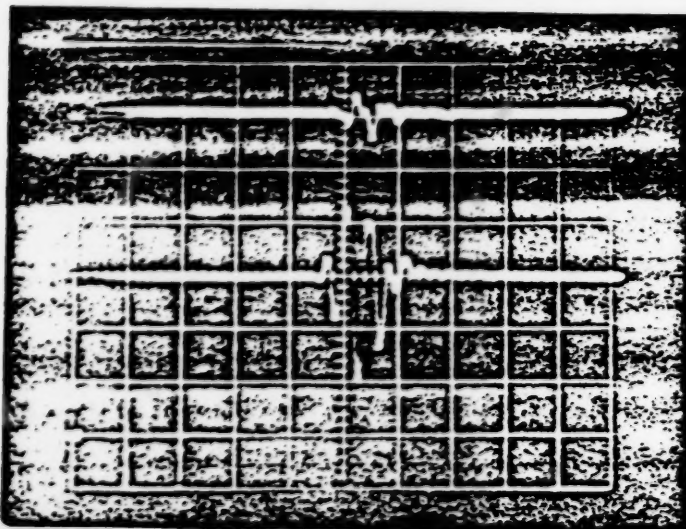


12B

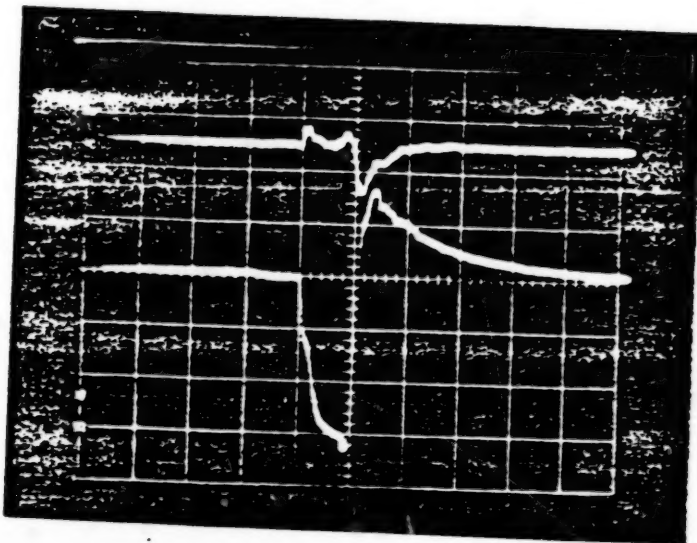
Lower Trace-marked rf

0.50V/div

Time Base-50 ns/div

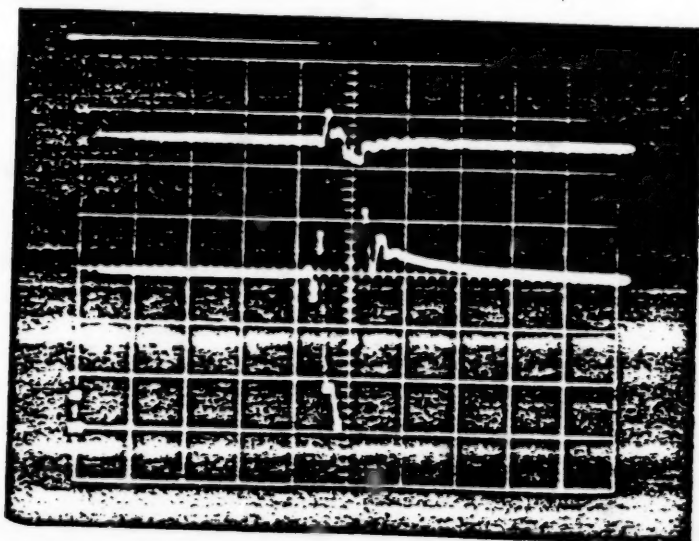


12C



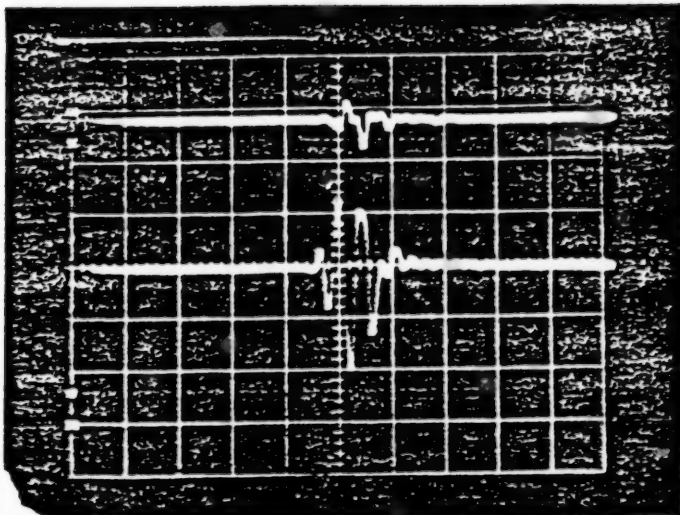
13A

5030A Pulser
 100 MHz Delay Probe
 Cable Length 7 cm
 Upper Trace-Gated rf 50mv/div.
 Lower Trace-Marked rf 0.5V/div.
 Time Base - 50 ns/div.
 1st Reflection
 Damping 500 Ω AT.L. 2db



13B

3rd Reflection
 Cable Length 7 cm
 Time Base - 50 ns/div.



14A

5030A Pulser

Cable Length 87 cm

75 MHz Delay Probe

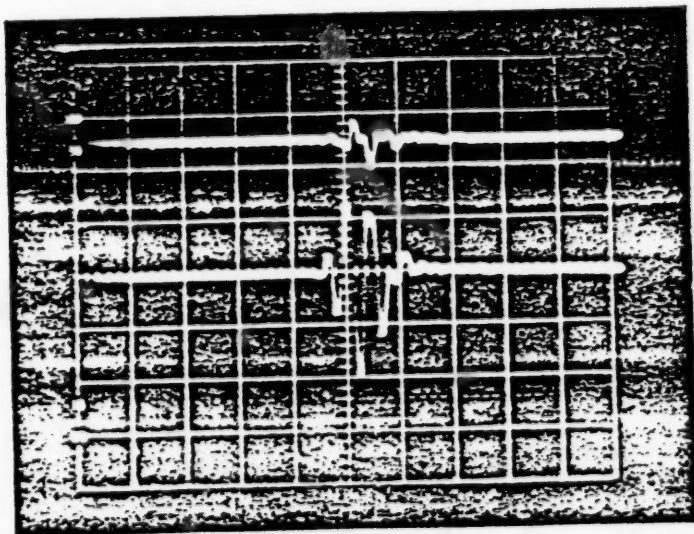
Upper Trace-Gated rf 50 mv/div.

Lower Trace-Marked rf 0.5 v/div.

Time Base 50 ns/div.

3rd Reflection

Damping 500Ω AT.L. 2db



14B

Cable Length - 107 cm

3rd Reflection

Time Base 50 ns/div.

- (5) the 3rd, 4th, etc. reflections showed harmonic content (splitting of the cycles) and this effect increased with increasing cable length (7 cm - 107 cm 50 μ s).
- (6) both instruments showed little variation of frequency (about 2%) with cable length (7 cm - 190 cm 50 μ s).

VI SIGNAL-CLEANING BOARD

Electronic problems will probably be a part of the development of ultrasonic testing at higher than commercial frequencies. The pulser-receiver, custom built by Panametrics has several deficiencies. One of them is the gate system; the so-called stepless gate is not stepless enough and discrimination against signals outside the gate is inadequate: i.e., the driving pulse spills over into the gated output as a 150 mV spike. The builder claimed that nothing could be done about it but we have found two options for rectifying the problem. One is to cascade another gate right inside the ultrasonic tester and another is to build an external gate in one of the signal processing boxes. We opted for the latter, but have had no success yet. Eventually we will overcome the problem which allows us to analyse signals which are not influenced by a false 150 mV spike. We think that ≤ 300 mV signals are currently impaired. Small defects often give reflections of 50 mV which the unit cannot pick up, nor can the analyzer analyze them.

It is important that this deficiency is rectified.

VII CONCLUSIONS

As a result of investigations conducted between April 1982 and March 1983, the following conclusions can be made;

- (a) a large number of sized defects have been put into plate glass and are available for assessing the performance of the newly-built scanner and the experimental transducers under development.
- (b) a new accurate scanning system has been designed and built and its auxiliary computer controls have been acquired.
- (c) an approximate physiomathematical model for the scattering from small defects of US signals from a focused pulsed transducer has been outlined.

- (d) techniques for synthesising superior PZT 4 and SPN ceramics have been developed and will now be applied to PZT 5 and PZT 7. A transducer of high power has been made from McMaster PZT 4.
- (e) the influence of cable length on transducer performance has been assessed and has been found to be minimal.

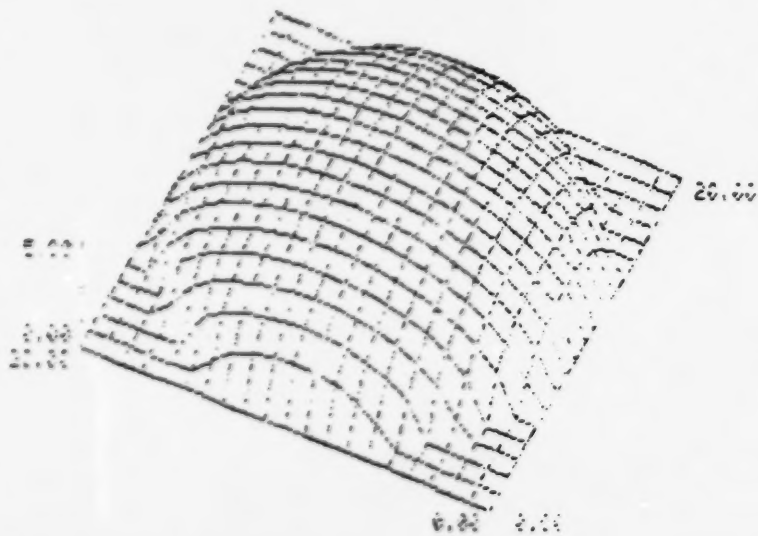
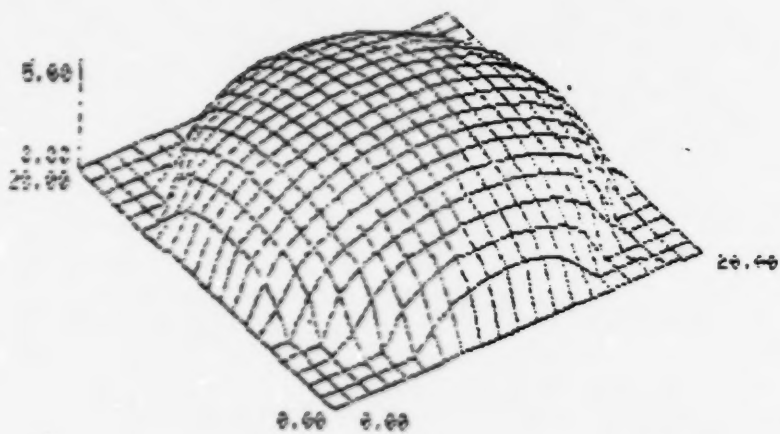
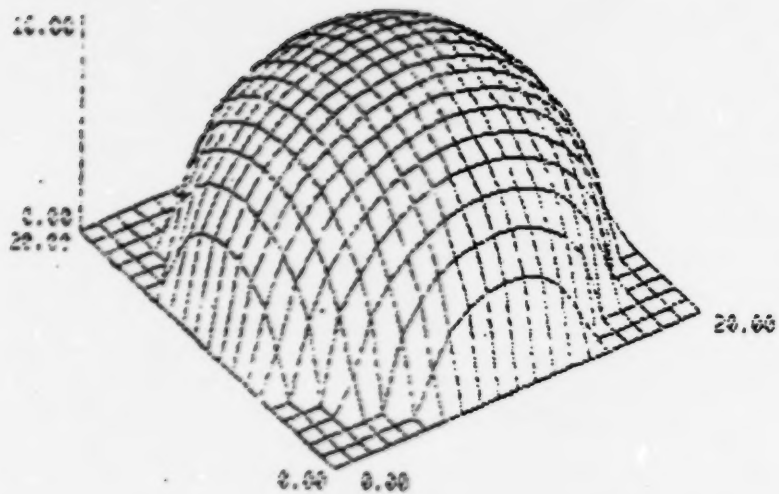
APPENDIX

COMPUTER PROGRAMMING

Most programs written for scanner control and equipment interface have been written in MACRO-11, the machine language of the PDP11 family. As such they are machine dependent as well as device dependent. For this reason, they have not been included in this report. However, a few FORTRAN IV routines have been written and can be more generally applicable. Of specific interest is a three dimensional plotting routine which uses the specific features of the VT125 graphics video terminal and interface to an LA34 graphics hardcopy terminal. The VT125 REGIS graphics commands provide the ability to effect hidden line plotting for any single valued function in X and Y. This condition is of course met for scan data where each point on the scan can have only one value. This subroutine named PLOT 3D, permits rotations of between 0 and 90° about the Z axis and 0 and 90° of tilt upward. A real array of 75 x 75 is required to be dimensioned in the user program and placed in a COMMON block named ARRAY along with two integer variables which define the number of X and Y axis grid points for which the function is defined. All points on the grid must be defined. Numeric labelling of the axis is performed by the use program defining a COMMON block called LABELS which contains three integer control variables for the Z, Y and X axis labelling followed by the real values for the maximum and minimum Z axis values, maximum and minimum Y axis values and maximum and minimum X axis values. The three control values enable labelling on their respective axis if the value of that control variable is non-zero. Furthermore the calling routine must pass, in a parameter list to the subroutine, the angle of rotation about the Z axis as a real value, the angle of tilt as a real value and a plotting mode control as an integer value. In this version the mode control will rescale the screen to match the scaling of the hard copy printer when it is a non-zero value. The subroutine does not modify the values in the Z axis array passed to it so that all future calls using the same array will be referenced to the same X and Y axis. Scaling of the screen is performed so that all points in the array fit on the screen vertically and the scaling of the X and Y axes is performed to provide a square image of the grid regardless if the number of X axis elements is different from the number of Y axis elements. The subroutine is not capable of sending the screen display to the hard copy part, this must be done by the calling program through the appropriate REGIS command. Furthermore, labelling of the axes with

text is not performed by the subroutine.

Sample hardcopy plots of regular functions have been included to illustrate the features of this subroutine.



SUBROUTINE PLOT3D(U,V,ISMODE)

This routine takes an array Z of size 75X75 representing points on a surface at regular intervals along the X and Y axes. NX gives the number of points along the X axis; and NY gives the number of points along the Y axis. The array Z is passed in a COMMON block named ARRAY (really original) along with the parameters NX and NY. Since NX and NY are integers the X and Y axes must have been pre-scaled.

The subroutine takes two angles U and V in degrees then rotates the display. Angle U represents the rotation in the plane perpendicular to the screen. Angle V is rotation of this plane about the horizontal axis of the screen. The display will be scaled and shifted to fit on the screen. The matrix Z is unaffected by this process.

For now assume that all U angles will be $0 < U < 90$. To assure that the XY plane is square when tilted 90 degrees (ie $V=90$) the maximum width at $U=45$ must be 469 pixels (the height of the screen)

```

BYTE ESC
DIMENSION IXP(75),IZP(75)
COMMON/ARRAY/Z(75,75),NX,NY
COMMON/LABELS/IWZ,IWY,IWX,ZUPPER,ZLOWER,YUPPER,YLOWER,
1           XUPPER,XLOWER

```

Vectors IXP and IZP represent the screen positions of the previous NX points plotted

```

DATA DTR/1.745329E-2/,SHGT0/479./,SLEN/767./,ESC/"33/
1,SQRT2/1.4142136/,ZSHIFT/20./
SHGT = SHGT0 - ZSHIFT

```

DTR is used to convert degrees to radians
 ZSHIFT is the offset at the bottom of the screen
 SQRT2 is the square root of 2
 SHGT0 is the screen height in pixels
 SHGT is the screen height in pixels minus ZSHIFT
 SLEN is the screen length in pixels

Calculate the rotation matrix from the angles

```

UR = U*DTR
VR = V*DTR
COSU = COS(UR)
SINU = SIN(UR)
COSV = COS(VR)
SINV = SIN(VR)
NXM1 = NX - 1
NYM1 = NY - 1

```

Find the maximum and minimum screen width values and the X-axis offset (XOFF) and scaling factor XSCALE

Since the array need not be square (ie NX neq NY)

```

RNM1 = RNMAX - 1.
XSL = RNMAX / NX
YSL = RNMAX / NY
XSCALE = SHGT / (SQRT2 * (RNMAX-1.))
XOFF = -RNM1 * SINU - 150. / XSCALE

```

Find the maximum and minimum ZS (horizontal screen value)
 z-axis offset (ZOFF) and the scaling factor ZSCALE

What I want to do here is find the maximum and minimum
 Z values. The minimum value will be used as an offset
 so that as far as this routine is concerned the Z values
 will be positive. The maximum value will be used for
 an initial ZS scaling factor.

```

ZMAX = Z(1,1)
ZMIN = Z(1,1)
DO 3 I = 1, NX
DO 3 J = 1, NY
IF(Z(I,J) .GT. ZMAX) ZMAX = Z(I,J)
IF(Z(I,J) .LT. ZMIN) ZMIN = Z(I,J)
CONTINUE
ZOFF = ZMIN
DZCOSV = ( ZMAX - ZMIN ) * COSV
ZSCALE = ( SHGT - RNM1 * COSU * SINV * XSCALE ) / DZCOSV

```

Change the ZSCALE value to make a square plot
 in DECUG only

```

IF( ISMODE .EQ. 0 ) GO TO 31
IF( V .EQ. 90. ) GO TO 32
ZSCALE = XSCALE * 1.0824 / COSV
GO TO 32

```

Now to proceed with the scaling of the Z axis
 What I must do is find the scale factor, ZSCALE,
 which keeps the entire plot within the bounds of the
 screen. But this value will change with the angles
 selected. The first guess at a scaling factor is
 to assume that the maximum Z value will run from
 top to bottom, then adjust the scale factor if a
 calculated ZS exceeds the maximum height SHGT.

```

21 ZSMAX = SHGT
DO 30 I = 1, NX
XSINU = (I-1) * COSU * XSL
DO 30 J = 1, NY
ZF = (Z(I,J)-ZOFF) * COSV
IF( ZF .EQ. 0. ) GO TO 30
ZXYP = ((J-1)*COSU * YSL * XSINU) * SINV * XSCALE
ZS = ZF * ZSCALE + ZXYP
IF( ZS .LE. ZSMAX ) GO TO 30
ZSCALE = (SHGT-ZXYP) / ZF
CONTINUE
CONTINUE

```

Prepare to plot by switch the screen to ReGIC mode
 Define the screen to have the origin at the lower
 left hand corner
 and erase the screen first.
 Then position the beam at the first point

```

YCOSU = NYK1 * COSU * YSL
XSINU = XNM1 * SINU * XSL

```

3

R-axis - [IXEX,IXEZ] & [IXYSX,IXYSZ]

Z-axis - (IYEX,IZUZ) & (IYEX,IYEZ)

Start by drawing the line furthest from the viewer
and set up vectors IXP and IZP

Now as each point on the screen is calculated (IXN,IZN) a line is drawn from it to the corresponding point on the line behind it (given by IXP(i),IZP(i)); then a line is drawn from (IXN,IZN) to (IXP(i+1),IZP(i+1)) is the previous point. Of course for the first point on a new line only a line from it to the point on the previous line is drawn. The new point then replaces IXP(i) and IZP(i). As shading is done in replace mode any lines 'below' the new lines will be erased.

This is for the first point on a new line

SECRET

```
WRITE(7,702)IXP(SX),IZP(SX),IXN,IZN
```

$\frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} f(x) \delta(x-a) dx = f(a)$

$$ZP(RN) = ZN$$

23 1 8 = 1351, 2, -1

$$YML = ((K-1) * CDSU * XGL - YSIN * XOFF) * XSCALE$$
$$ZRN = (ZMAX - ZMIN) * ZDSV * ZSCALE$$

1 - "CUBAN" + (K-1) SINGU *XOL 1 - SINGU * XEDALE

2 754157

$$X_{K+1}^{\text{new}} = \begin{cases} X_K^{\text{old}}, & \text{if } |X_K^{\text{old}} - X_K^{\text{new}}| \leq \epsilon \\ X_K^{\text{new}}, & \text{otherwise} \end{cases}$$

11. '07'13' '13'24(8'353511.01)B'13' '13'11B'

SUBROUTINE PLOT3D(U,V,ISMODE)

This routine takes an array Z of size 75X75 representing points on a surface at regular intervals along the X and Y axes. NX gives the number of points along the X axis; and NY gives the number of points along the Y axis. The array Z is passed in a COMMON block named ARRAY (really original) along with the parameters NX and NY. Since NX and NY are integers the X and Y axes must have been pre-scaled. The subroutine takes two angles U and V in degrees then rotates the display. Angle U represents the rotation in the plane perpendicular to the screen. Angle V is rotation of this plane about the horizontal axis of the screen. The display will be scaled and shifted to fit on the screen. The matrix Z is unaffected by this process.

For now assume that all U angles will be $0 < U < 90$. To assure that the XY plane is square when tilted 90 degrees (ie $V=90$) the maximum width at $U=45$ must be 469 pixels (the height of the screen)

```

BYTE ESC
DIMENSION IXP(75),IZP(75)
COMMON/ARRAY/Z(75,75),NX,NY
COMMON/LABELS/IWZ,IWY,IWX,ZUPPER,ZLOWER,YUPPER,YLOWER,
1           XUPPER,XLOWER

```

Vectors IXP and IZP represent the screen positions the previous NX points plotted

```

DATA DTR/1.745329E-2/,SHGT0/479./,SLEN/767./,ESC/"33/
1,SGRT2/1.4142136/,ZSHIFT/20./
SHGT = SHGT0 - ZSHIFT

```

DTR is used to convert degrees to radians
ZSHIFT is the offset at the bottom of the screen
SGRT2 is the square root of 2
SHGT0 is the screen height in pixels
SHGT is the screen height in pixels minus ZSHIFT
SLEN is the screen length in pixels

Calculate the rotation matrix from the angles

```

UR = U*DTR
VR = V*DTR
COSU = COS(UR)
SINU = SIN(UR)
COSV = COS(VR)
SINV = SIN(VR)
NXM1 = NX - 1
NYM1 = NY - 1

```

Find the maximum and minimum screen width values
and the X axis offset (XOFF) and scaling factor XSCALE

Since the array need not be square (ie NX .ne. NY)
it is necessary to determine the effect of rotation
on a square matrix. So RNMAX is the largest of

POOR

QUALITY

ORIGINAL

